A SHORT REVIEW OF SOME RECENT APPLICATIONS OF PHOTONIC CRYSTALS

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ABSTRACT

Photonic crystals (PhCs) are still a topic of ongoing research worldwide. Photonic crystals (PhCs) are artificial dielectric structures that control light passage by varying the refractive index randomly and periodically. PhC-based photonic devices can benefit from the capacity to control the electromagnetic field's propagation in these structures. This unique property with a miniature size can be used to make dense integrated circuits. However, as PhC technology is still relatively new, more research on this subject is necessary. In order to summarise the latest advancements in this popular subject, I have reviewed the most widely used and essential optical components based on PhCs in this work, including logic gates, sensors, amplifiers, and absorbers for solar thermophotovoltaic applications. These devices exhibit superior performance than traditional photonic devices.

KEYWORDS: Photonic Crystals, Logic Gate, Sensor, Amplifier, Solar Cell

INTRODUCTION

Since the discovery of photonic crystal (PhC) in 1987, reported by Yablonovitch[1] and John[2] it has attracted a lot of attention[3]. Fundamentally, PhCs are a kind of optical structure made up of a periodic modulation of the dielectric function dispersed within a certain geometric lattice. When electromagnetic waves are launched into the PhC, the coherent scattering processes will impact them because of the periodicity. Within the structure, waves of specific frequencies are propagated or reflected by the scattered waves due to the constructive and destructive interferences between them. Photonic bands (PB) and photonic band gaps (PBG) correspond to the permitted and prohibited frequencies, respectively. As a result, an electromagnetic wave that strikes a crystal with a frequency inside the PBG is fully reflected. In contrast, the frequency will propagate within the PhC if it is inside the permitted region (PB)[4,5]. PhCs are like optical semiconductor devices, it is possible to tailor their geometrical features to create conductors or insulators of electromagnetic waves. Photonic crystals can be classified into three types: one-dimensional (1D), two-dimensional (2D), and three-dimensional (3D) shown in figure 1. The dielectric function in 1D PhCs is periodically modulated in one direction, whilst the medium is uniform in the other two dimensions. Only the dielectric materials, layer thicknesses and the number of layers inside the period can be changed in this instance, leaving relatively few other options[6]. In a two-dimensional photonic crystal structure, the dielectric function is periodic in two dimensions, while the medium is uniform in the third. Thus, changing the dielectric materials, lattice geometry (square, hexagonal), lattice constant and dielectric form (square, ellipses, triangle) may occur in a wide range of configurations[7].

Nevertheless, two configurations are frequently utilized for technological reasons: square and hexagonal lattices. A silicon substrate with etched holes or a system of dielectric rods in air are excellent examples for both situations[8]. By varying the refractive index in each of the three spatial directions, 3D PhCs may be created[9]. An example of this would be a stack of spheres made of a dielectric substance submerged in air. All three directions exhibit dielectric modulations in three-dimensional photonic crystals. In contrast to 1D or 2D PhC, there are a lot more possible configurations with that. Despite being very omnipresent in nature, these 3D structures are more challenging to create. As we know band structure is very useful in understanding the properties of the structure in solid-state physics[10]. It represents the connection between the characteristics of Phc and properties of propagation and reflection. It is like a semiconductor controls photons in place of electrons in it.

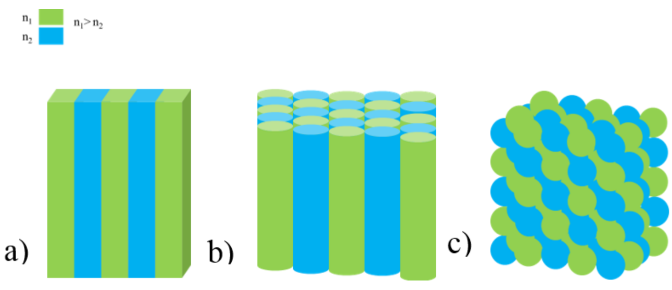

Figure 1: Recreated graphical illustrations based on work[45] a) 1 D PhC b) 2 D PhC c) 3D PhC with varying refracting indices respectively.

So, light can be used as an information carrier instead of electrons and photon-integrated circuits can be made in the nanometer range. Light having greater speed in dielectric material than electron can carry more amount information per second. The bandwidth of dielectric material is significantly greater than metal. Photon has more advantages than electrons because its non-interacting property reduces energy loss[1,2,11]. Because of the possibility of creating a PBG, it could have the

ability to affect how light travels. PhCs have several notable uses, such as negative self-collimation[5], light bending[12], optical diodes[13] and negative refraction[14]. In the next sections, some of the recent popular PhC-based devices using this property have been reviewed.

Phc based Logic gates:

These days, PhC logic gates are among the most important optical media that drew researchers to create optical processors[15]. PhC structures can reduce the optical logic gates' (OLGs') size to the wavelength order. These gadgets frequently use microwatts of power and respond in less than a few picoseconds, contributing to their high switching speed. It has been used for the advancement of making integrated optical circuits. Digital information can be exchanged at lightning speed to the electronic processor using optical fibre. However, the highest switching speed for electrical logic gates is equal to 50 ps with a typical one-switching power of 0.5 mW. The p-n junction and interlinking capacitances affect the switching speed of logic gates built on semiconductors[16], while the speed of light passing through PhC-based OLGs is the only factor limiting the switching speed. OLGs are capable of performing several logic operations and have a wide range of applications in optical communication. For instance, the AND logic gate can be used for data integrity checking, packet header adjustment, address recognition, and even as a sampling gate in optical oscilloscopes. XOR gate formed by PhC can be used to perform an assessment of data patterns for address identification, packet switching, data encryption/decryption, the parity search and optical generation of pseudorandom patterns. The NOT gate possibly is employed as an inverter or switch and the threshold detector operation is done using the XNOR logic gate. PhC OLGs were initially presented in 2006[17], when researchers proposed and quantitatively created an AND gate based on a PhC interference WG between a bent WG with three embedded Kerr-type nonlinear rods and a T-branch.

For the realization of all-optical devices, PhCs are offered a new avenue[18–20]. These devices control the flow of light by using the periodic arrangement of crystals with different refractive indices. Strong light confinement, small size and fast light propagation, fast response time, broad bandwidth, and low power dissipation are only a few of the outstanding features of PhCs.[21]. Silicon PhC waveguides are suitable for the design of combinational and logical optical circuits because of their great light confinement. PhC energy bandgaps are caused by the periodic arrangement of atoms in a crystal. PhCs can also be used to create the fascinating phenomenon of blocking light transmission by optical switching methods[22]. In this manner, PhCs have been considered by researchers[23] as a potential structure for use in arithmetic logic circuits as a half-subtractor. Bahabady et al.[24] suggested a design of a structure to be realized for the XOR gate. It is shown in Figure 2. Three waveguides and two nano-resonators made up the structure, which was situated at the T-shaped junction. The nano-resonators were chosen to be 30 nm in size because this size allowed for the best optical transmission from the input waveguides to the output and the highest output power in the equivalent state. I1 and I2 were used to receive the input signal, and O1 was used to receive the output signal. One of the input ports had been utilised to control the signal if this structure was being used as a NOT logic gate.

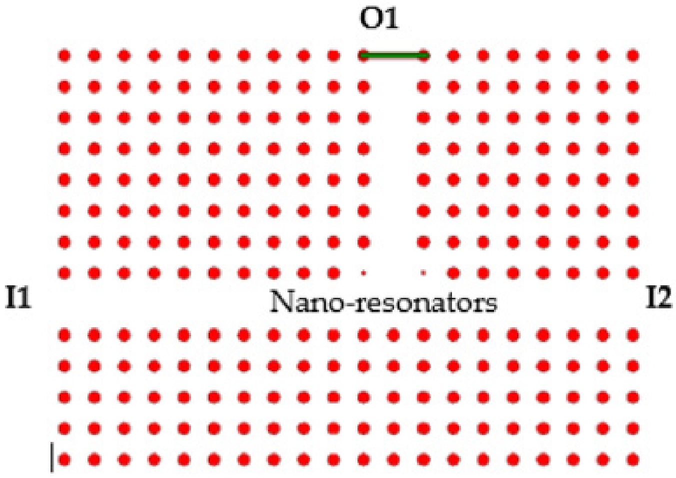

Figure 2: XOR gate made with PhC.Figure adapted from Bhabady et al[24] under the CC BY-4.0 licence.

A half-subtractor is essential for calculating addresses and increment or decrement operators. The half-subtractor is the simplest basic combinational logic circuit used in digital electronics. This circuit generates two output bits (difference and borrow) and permits the subtraction of two binary digits.

Similarly, Rao et al.[25] used square lattice-type silicon rods and a combination of T- and Y-shaped waveguides to make the all-optical MUX. Here, reverse reflection which reduces power loss is achieved by using silicon rods.

Rao et al.[18] Also, they suggested a reversible logic gate for a lossless digital system. It is amazing because it reduces heat generation and power consumption in a photonic-integrated system. They used two-dimensional PhCs to design the Toffoli and Feynman logic gates for low-power integrated circuits. These optical reversible gates are constructed without the use of nonlinear materials, and their design is verified using commercial software based on FDTD in the 1550 nm wavelength range. Rachana et al.[26] then suggested a 3-input AND logic gate which makes use of a silicon-based, 2D photonic crystal in the shape of a T. Error correction, performance recognition, code conversion, arithmetic operations, and encryption/decryption are just a few of the uses for this gate. The 3-input AND logic gate has a respectable size of 8.4 μm × 5.4 μm. Additionally, all-optical photonic devices for high-speed optical computing and large-scale integration were proposed by Rao et al[20]. Using a single structure, they have developed and examined the NOR, NAND, and XNOR logic gates.

Logic gates (LG) with different mechanisms are described below:

1. **LG Based on Self-Collimation (SC):**
   An incident light beam is partially reflected and partially transmitted when incident a PhC structure with a self-collimated region. As a result, there is a phase shift between the transmitted and reflected beams. The radius of the SC PhC region's dielectrics determines this phase difference.

The reflected and transmitted light beams may interfere either constructively or destructively if another beam of light with the proper phase is launched. Adjusting the dielectrics' radii and adding various phase shifts between the incident beams at the input faces will allow for the achievement of SC PhC.All optical logic gates have been made using this technique[27,28].

2. **LG Based on MMI (Multi-Mode Interference):**
   Binary Phase Shift Keyed (BPSK) signals can be used for this, as the output signal's amplitude, independent of its phase, determines the output logic value. When the input signals have the correct signal phases, they interact in the MMI area to either eliminate the signal creation, which corresponds to logic 0 at the output port or generate a signal corresponding to logic 1.

   As shown by Ishizaka et al., Liu et al., and Tang et al.[29–31], the logic gates can be realised by choosing the appropriate parameters in addition to the input signal phases.

3. **LG Based on Waveguide Interference Paths:**
   This method of projecting logic gates in photonic crystals is straightforward, practical, and efficient. In this method, if there is constructive interference between the input waveguides, the high transmission condition (logic 1) is assured. This is achieved by creating an intersection point where the input signals have a phase difference of $2k\pi$ and the path difference is 0.

   On the other hand, destructive interference between the input signals occurs when the planned path difference is one lattice constant, resulting in a phase difference of $(2k+1)\pi$ and a low transmission state (logic 0). Fu et al. have theoretically implemented the OR, XOR, NOT, XNOR, and NAND gates using these methods[32].

4. **LG Based on the Kerr Effect**
   The structure must have a waveguide-cavity linked system added, and the input power must be carefully chosen, to implement logic circuits that use the Kerr effect on PhC. Yanik et al.[33] suggested a high-contrast all-optical bistable switching system using this method.

Sensor:

Photonic sensors have grown significantly in recent years due to the increasing need for sensing applications in various industries, including aerospace, food quality control, healthcare, and defence. PBG, which stops light from propagating at particular wavelengths, can be created by engineering the PhC surface, a periodic-modulated dielectric nanostructure material [34–36].

In life science research, the local optical modes of the PhC surface can therefore be utilised as a very sensitive, label-free platform for biosensing and bioimaging[37]. Using third-generation PhC-enhanced microscopy, surface-absorbed live cells[38] (including apoptosis, chemotaxis, and cell adhesion) and nanoparticles were captured without labels. The photonic crystal (PhC) interacts with the resonant mode to enhance the electric field. This can be excited by a laser, enabling fluorescence imaging. High-performance sensing devices can be implemented in an interesting way with PhCs. Numerous photonic sensor configurations have been extensively studied and used in sensing applications[39,40]. PhC-based refractive index (RI) sensors are being studied by researchers worldwide, and numerous types of advanced sensor designs, including interferometers[41] and integrated microcavities[42] have been suggested for RI sensing applications. These sensors have many advantages, such as high sensitivity and low sample preparation that do not require fluorescent labelling.

The use of chemical analytes in the measurement of a bulk solution's RI fluctuations makes the sensing technique possible. Applications to differentiate the concentrations of biological samples in gaseous and aqueous environments have been contemplated. In practice, these sensors can be used to count the surface or cubic density of molecules and proteins.

Many sensor systems have recently made extensive use of PhCs[43,44]. Because of its small size and great sensitivity, researchers have been interested in different types of RI sensing devices based on the metal-insulator-metal (MIM) plasmonic WG structure[40]. These sensors have a very high sensitivity because of the significant interaction between the surface plasmon polariton (SPP) wave and the surrounding medium[45].

However, these devices are rarely experimentally studied because of the difficulty and inaccuracy of fabricating these miniature devices on a thin metal layer. A 2D layered nanomaterial (graphene, MoSe2, MoS2, WSe2, and WS2) decorated 1D PhC refractive index sensor based on the Kretschmann configuration was proposed by Maurya et al. in 2018[44]. Because of its strong adsorption, the 2D nanomaterial exhibits an excellent sensing response.

Since some hazardous gases (such as CO2, CH4, and CO) show absorption lines in the mid-IR wavelength area, gas sensors based on PhC are suggested for the mid-IR range[46]. A PhC air-slot cavity-based high-precision gas index sensor with a 510 nm/RIU sensitivity was suggested[47].

A surface plasmon resonance (abbreviated SPR) nanocavity antenna array with a high sensitivity of 3200 nm/RIU is suggested for gas sensing applications in a paper[40]. It is reported that a guided-mode resonance gas sensor has a sensitivity of 748 nm/RIU[48] and a fibre-optic Fabry-Perot gas sensor has a sensitivity of ~ 1550 nm/RIU[49]. In[50], PC/Ag/graphene as an RI sensor based on the Tamm state with a sensitivity of 1178.6 nm/RIU was reported.

PhCs have also become fairly common in applications involving chemical and biological sensing. Technically speaking, PhC-based optical sensors, such as integrated planar PhCs and PhC optical fibre, or PCF, are appropriate for label-free detection and multiplexing. For instance, Zou et al. published large-scale chip-integrated PhC sensor microarrays in 2012 and showed how they might be used for biosensing on a platform based on

SOI[51]. In 2013, Lu et al.[52] also reported an integrated temperature sensor based on an enhanced pyroelectric PhC. The pyroelectric effect of lithium-niobate, in which an appropriate air-membrane PhC cavity has been created, allowed the devices to produce the sensing response. Shafiee et al. used nanostructured PhCs in 2014 to identify and quantify intact viruses (HIV-1) from physiologically relevant materials without the need for labels[53].

Amplifier:

A photonic crystal-based optical amplifier is a type of optical amplifier that enhances and controls the amplification of light signals using photonic crystal. These amplifiers are crucial in the domains of optical communication and photonics.Periodic structures having alternating regions of high and low refractive indices are known as photonic crystals, and they may be able to regulate the way light travels at particular wavelengths. PhC-based optical amplifiers have special features like wavelength selectivity, enhanced light-matter interaction, efficient amplification, compact size, tuneable gain, and reduced noise. It is possible to specifically design the properties of the photonic crystal to create amplifiers that are very selective for particular wavelengths or narrow wavelength bands. WDM systems, fibre optic network signal amplification, and the creation of tiny and efficient optical amplification components for integrated photonics are some of the optical communication applications for photonic crystal-based optical amplifiers.

In recent years, PhCs have been successfully used in a variety of optoelectronic devices, including semiconductor lasers[54], optical waveguides[55], semiconductor optical amplifiers (SOAs)[56], and all-optical switches[57]. By modifying the semiconductor optical amplifier device using a PhC structure, a novel device called a photonic crystal semiconductor optical amplifier (PhC–SOA) is designed[58]. This device utilises both the advantages of PhC architecture and SOAs. The enhanced light-matter interaction in PhC structures allows for a significant reduction in the SOA length[59,60]. Reduced electrical interference, extremely fast reaction times, superior computation accuracy, and shorter sensor length and load are some of the benefits of the optical current amplifier over traditional current-sensing technologies. Other than that, the primary applications of optical amplifiers are in communication and optical sensing[55].

Solar cells:

In recent years researchers have widely exploited unique properties like PBG and slow photon effect to improve the development of solar cells. Photon dispersion and propagation in solar cells may be effectively modulated by the introduction of PhCs. Therefore, a thorough understanding of the optical properties of PhCs is essential to enhance the efficiency of photoelectric conversion. PhC structures are now used in dye-sensitized solar cells (DSSCs) and quantum-dot-sensitized solar cells (QDSSCs), although they are used in very small amounts in the field of perovskite solar cells (PSCs)[61]. In this section, the different types of application PhCs in sensitized solar cells and silicon solar cells, and their possible limitations and advantages will be discussed. Due to the unique property of PBG, PhCs have contributed to technical advancement in light manipulation in special ways. Selective sunlight absorption is facilitated by the integration of PhCs with an appropriate absorber. The absorption cutoff may be modified by changing the periodic structure's size, which will move the PBG. PhCs can also improve absorption by quality factor matching[62,63]. The PhC offers the benefit of incorporating diffraction, where the photon momentum (k) can be dispersed away from the specular path with k = ki + g, where g is a reciprocal lattice vector and ki is the incident wave vector. A novel strategy has been set up to enhance light-trapping in crystalline silicon solar cells using a PhC back reflector in conjunction with a reflection grating[64]. A spectrally selective solar absorber is a crucial part of solar thermophotovoltaic (STPV) systems[65].It is shown that a superlattice PhC design can be used to adjust and expand a solar absorber's high absorption range. Two superposed lattices—that is, a lattice with multiple cavities per unit cell—with varying cavity radii make up the architecture. Here, the high absorptivity spectral range that may be customised by modifying the cavity geometry parameters is increased by the contributions. By absorbing solar photons as heat and releasing them as thermal radiation, which is subsequently converted into electron-hole pairs using a low-bandgap photovoltaic (PV) medium, STPV converts sunlight into electricity[66].

CONCLUSION

In this article, I have presented an overview of photonic crystals and their recent application of it. Recent applications of PhC devices in the field of Logic gates, sensors, amplifiers and solar cell were reviewed here. Readers are given a basic knowledge of the importance of this research topic and its history through this review. It is an extremely adaptable technology that may be used in many aspects of our daily lives due to its compact, affordable, and tiny equipment that allows for the modification of electromagnetic field propagation. The selective absorption of solar energy can be enhanced by the combination of PhCs and a suitable absorber. To attain excellent performance and durability, several absorbers have been proposed and are now being used. This article summarises several extremely sensitive sensors that are based on different PhC setups. Certainly, specialists and early researchers interested in this area can recognize the unique qualities and versatility in the structural design of PhC-based devices, expanding their knowledge and perspectives to explore further applications.

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